Global Topology Optimization of Fluid Motions in Microchannels

著者	吉村 光生
number	62
学位授与機関	Tohoku University
学位授与番号	工博第5454号
URL	http://hdl.handle.net/10097/00124774

	よしむら　みつお
氏　　　　　　　名	吉　村　光　生
授　与　学　位	博士（工学）
学 位 授 与 年 月 日	平成３０年３月２７日
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指　導　教　員	東北大学教授　大林　茂
論 文 審 査 委 員	主査　東北大学教授　大林　茂　東北大学教授　岡部　朋永 東北大学教授　太田　信　東北大学准教授　小宮　敦樹 東北大学准教授　下山　幸治

論 文 内 容 要 旨

Topology optimization is one of the most flexible optimization methods which can not only modify its shape but also allow the connectivity (i.e. topology) of the object to change independently of the initial topology information such as connectivity of the design domain. Over the past three decades, topology optimization has been mainly studied in structural design and the methods are matured to a level where it can be applied to real-world engineering problems. In general, topology optimization involves a large design space because of a high degree of freedom for shape and topology representation (i.e., the number of design variables is often equal to the number of elements in the finite element mesh). In order to solve such large scale problems, the gradient based approaches are often employed since they can handle a large number of design variables and find an optimum in a short time as long as the sensitivity (aka derivative) of the objective function is available. However, the application of topology optimization to the heat and fluid problems is still limited since the objective function in these problems tends to be a multi-modal function or non-differentiable, which is difficult to solve by conventional gradient-based methods. This thesis focuses on topology optimization of micro heat sink and micromixer. The purpose of this thesis is to develop a topology optimization method for fluid and thermal problems using genetic algorithm and to clarify the fluid motions in microchannel. In order to apply genetic algorithm to fluid and/or thermal problems efficiently, the Kriging model is employed to reduce the computational cost for function evaluation. Moreover, this thesis proposes original representation methods which enable us to represent a complex configuration including topological change with a reasonable number of design variables.

In Chapter 2, topology optimization is applied to design a heat sink. The configuration of the channel is decided by topology optimization using the level-set based representation method. In this chapter, we propose a two-phase representation method consisting of two partial differential equations. The first equation gives the crude distribution of the level-set function in the entire design domain. The crude level-set distribution is so steep that the wall of the projected two-dimensional flow

channel is often wavy. In order to relax such a steep distribution of the level-set function, the second equation, which is expressed as the Helmholtz equation, is applied. The Helmholtz equation introduces two independent weights for *x*- and *y*-directions. These weights play a key role to smoothen the distribution. That is, we can control the steepness of the distribution in higher degree of freedom and represent the change of shapes in addition to the topological change by just introducing two additional design variables. Firstly, the proposed method is applied to a single objective optimization problem to maximize heat transfer performance. In the case studies, GA found several local optima in addition to the global optimum, which suggests that the objective function is a multi-modal function and the effectiveness of using genetic algorithm. The local and global optima indicate that the size, number, and shape of the heat source(s) put inside the channel are quite important for high heat transfer performance. More specifically, the shape of heat sources should form streamlined shape so as not to provoke flow separation. Secondly, the proposed method is applied to a multi-objective optimization problem considering minimizing pressure loss as a second objective function. The proposed representation method and the non-dominated solutions revealed that not only the topology of the channel but also their shape contribute to improve both objectives.

In Chapter 3, a two-phase flow problem to design micromixer is solved by topology optimization with genetic algorithm. Due to the small size of the micromixer, the flow in the microchannel is mainly dominated by laminar flow and the mixing is enhanced by the molecular diffusion. Since the molecular diffusion is a very slow process, it needs more time and longer channel length to complete mixing. Hence, the mixing must be enhanced by further mechanism in order to complete mixing in a short channel length and short reaction time. The key idea to enhance mixing is to increase the interface between two fluids. Micromixers can be classified into two types based on their mechanisms to enhance mixing; active and passive mixers. Active micromixers perturb the flow by external sources. Although active micromixers can improve mixing efficiency, most of them are complex to fabricate and operate. On the other hand, passive micromixers do not require external actuator and they enhance mixing by changing their geometries to generate convection. Then, the interface between fluids are stretched and folded and the efficient mixing is achieved. This study aims to enhance mixing by using configuration of grooves attached on the bottom of the channel. In order to represent complex configuration of grooves with a reasonable number of design variables, this study employs a representation method based on a graph theory. Two different design domains are considered; (1) convex case: grooves are attached toward outside of the channel, (2) concave case: grooves are attached toward inside of the channel. Three case studies are conducted in convex case to investigate the proper number of grooves and the influence of adopting different width for each groove. These case studies reveal that grooves should compose asymmetric configuration to enhance mixing through convection. Oblique grooves transport one fluid to the other fluid side and enhance mixing by distorting the fluid interface. Moreover, these case studies also reveal that the proper number of grooves where a global optimum may locate in close proximity. GA can explore and reach the global optimum more efficiently on the Kriging model constructed by the sample points with the proper number of grooves. In each case, GA found several local optima which indicate the objective function is a multi-modal function and revealed that the global optimum enhances mixing by not only distorting the interface but also splitting. Then, the proposed method is applied to concave case. Although the asymmetric configuration of grooves is essential to enhance mixing as well as in convex case, the local and global optima indicate that the configuration plays a different role compared with those of convex grooves. In this case, not only the oblique grooves but also the short lateral grooves also play a key role that stretching the fluid interface by velocity difference on the ethanol and water side. Then, the velocity difference leads to the folding of the fluid interface. The fluid interface is repeatedly stretched and folded in the mixer, which means that the contact area of two fluids is increased dramatically. Thus, although they needs high pressure, the mixing performance in concave grooves problem is much superior to that in the convex cases. The approach proposed in this chapter offered a novel aspect on application of GA to fluid topology optimization and showed promising potential for the design of micromixers. The designers can choose a proper micromixer based on their purpose; the convex grooves enhance mixing with modest pressure loss, and the concave grooves enhance mixing in shorter channel length at the cost of high pressure loss.

In Chapter 4, considering more practical situation, robust topology optimization of micromixer, which is an extension of the study in Chapter 3, is conducted. This chapter considers two different types of uncertainty, error in manufacturing and error in operation. Error in manufacturing is expressed as perturbation on dimensions of the grooves and error in operation is expressed as perturbation on the inlet fraction. The robust topology optimization is applied to the concave case conducted in Chapter 3 since the preliminary parametric study shows that the mixing performance of the concave case is very sensitive to the perturbation compared with the convex case. In order to clarify the relationship between the performance and robustness, GA is applied to solve the multi-objective optimization problem minimizing the mean and the standard deviation of the mixing efficiency. Since the robust optimization is inherently more expensive than the deterministic models and the cost often becomes prohibitive. In order to evaluate the structures considering uncertainties and to obtain their statistics, this study employs two-stage approach using two Kriging models. In the first phase, the Kriging model of the objective function in deterministic optimization (model 1) is constructed until the model satisfies sufficient accuracy. The additional sample points added in Chapter 3 are also included in the initial sample points of model 1 to obtain more accurate model and to facilitate the exploration. In the second phase, we first give perturbation to each sample points on the model 1 assuming each sample point follows a truncated normal distribution and calculate the means and the standard deviations of these sample points. Then, we construct the Kriging model for these means and standard deviations (model 2) and the Pareto front of the statistics are explored by GA. This chapter contains three case studies; two cases consider each uncertainty separately and one case considers both uncertainties concurrently. In the case considering error in manufacturing solely, the non-dominated solutions indicate clear relationship between dimensions and robustness. Several non-dominated solutions imply that relying on stretching and folding for high mixing efficiency is not preferable since such phenomena are quite sensitive to the perturbation on dimensions. In order to obtain the balanced solution, we could design a channel in which these phenomena occur less frequent. In the case considering error in operation only, the non-dominated solutions indicate that the topology of the grooving structure is more important than its dimension. In this case, high robustness could be achieved easily by design the configuration of grooves more symmetric. On the other hand, for high mixing performance, we could employ the long oblique grooves as auxiliary structures which push the interface toward the short lateral grooves for being stretched. Finally, in the case considering both uncertainties, we could exploit the insights obtained in the previous cases. In other words, following three factors are important to balance the performance and robustness; (1) the dimension of grooves should not be too high since stretching and folding are very sensitive to perturbation on the dimension, (2) symmetry of configuration which can ensure high robustness to the perturbation on the inlet fraction, and (3) the mutual relationship of short lateral grooves and long oblique grooves which makes the flow motion more robust to the perturbation on the inlet fraction and improves the mixing performance .

Consequently, this thesis proposes novel approaches of fluid topology optimization using non-gradient based method which is difficult to solve by conventional gradient-based approaches. The proposed methods are applied to the deterministic optimization of heat sink, micromixer and the robust optimization of micromixer. In single-objective problems, several local optima and global optimum are explored by GA and the fluid motions of each optimum are investigated. In multi-objective problems, the Pareto front is revealed so that a designer can choose arbitrary solutions among the non-dominated solutions based on their demand. The aforementioned results of global topology optimization offer specific guidelines to design efficient micro heat sink and passive micromixer.

論文審査結果の要旨

本論文は，熱流体または二相流を考慮した流路デバイスの抜本的性能向上を目的とした形状最適化について，最適化手法の中で，最も自由度の高いトポロジー最適化を遺伝的アルゴリズムで解く手法について論じたものであり，全編５章からなる。

第１章は序論であり，本研究の背景，目的および構成を述べている。

第２章では，ヒートシンクのトポロジー最適化について，Building-Cube Method を用いた熱流体場の解析手法と，遺伝的アルゴリズムをトポロジー最適化に効率よく適用するための形状表現手法を提案している。トポロジー最適化では物体形状が連続性の変化を含んだ複雑な変形を伴うことが一般的であり，Building-Cube Method は直交格子による解析を実現することからトポロジー最適化への応用に適している。提案手法では，形状表現にレベルセット関数を用いている。レベルセット関数では，物体の特性を関数の符号値に基づいて判定し，流体と固体の境界を明瞭に表現することができる。従来のトポロジー最適化では計算格子の各々が設計変数として扱われるため，自ずと設計空間は膨大なものとなるが，本論文の提案手法では，設計領域のレベルセット関数が Laplace 方程式に従うと仮定して，少数の代表的な設計変数で領域全体のレベルセット関数の分布を求めている。さらに，形状表現の自由度を高めるために Helmholtz 方程式によるフィルタリングを適用し，流路壁面の平滑化と流路内部構造の複雑化により高い熱伝達性能と低い圧力損失を両立する形状の創成を実現しており，非常に有効な手法を提案している。

第３章では，マイクロ混合器のトポロジー最適化を議論している。層流に支配されるマイクロ混合器は，短距離・短時間で混合を完了させるために対流を起こす手段を講じる必要がある。本論文では，流路底面に周期的な溝を取り付け，溝の配置問題をトポロジー最適化によって決定する方法を提案している。溝の表現はグラフ理論に基づき，グラフの各頂点の連結情報が溝に相当する辺として表される。遺伝的アルゴリズムが効率的に大域解を発見するための設計空間の注目すべき領域，すなわち溝の本数の決定法，及び，溝を取り付ける方向による混合への影響を考察し，混合が促進されるために重要な流体運動と，特に重要な溝配置を解明し，重要な成果を得ている。

第４章は，マイクロ混合器のトポロジー最適化において，実際の運用上典型的にみられる不確定性を仮定したロバストトポロジー最適化について論じている。不確定性として，流路造形時に生じうる寸法への製造誤差及び，運用上生じうる二流体の割合の変動を考慮し，それぞれが別々に，または同時に発生したときのマイクロ混合器の混合性能とそのばらつき（ロバスト性）について，遺伝的アルゴリズムによる大域的解探索によってトレードオフ関係を明示している。寸法の不確定性については，第３章で得られた混合を促進する流体運動に関する知見に基づいて，性能とロバスト性を両立する構造を論じている。流体の割合への不確定性では，溝の配置が重要であることを示し，高いロバスト性のためには溝の配置が対称にすることが望ましいと示している。さらに，二つの不確定性を同時に考慮した場合では，それぞれを独立に考慮した場合に得られた知見が有効であることを確認している。これらの成果より，本論文の提案するトポロジー最適化法は，現実の設計に対して非常に有効と考えられる。

第５章は結論である。

以上要するに本論文は，革新的な性能を実現する流路デバイスのトポロジー最適化について，大域的な解探索を実現することにより，設計者の様々な要求に応える設計案を提示することを可能とするものであり，最適化工学並びに航空宇宙工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。